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Microwave transducers for moisture content characterization of cultural heritage materials

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***Abstract* – This paper presents the design, fabrication, and test of a microwave transducer aimed at monitoring the moisture content in cultural heritage materials, which is a critical factor in the preservation of historic structures. Following the principle of "preventive restoration", the proposed sensor ensures noninvasive and contactless measurements, which are features highly desired for monitoring fragile and valuable structures. The proposed two-port device operates in the frequency range from 2.25 GHz to 2.40 GHz and is fabricated on a 1.6-mm-thick FR4 substrate using the versatile inkjet-printing technology. Samples, specially prepared for this research activity, are employed to test and characterize the response of the proposed sensor. The achieved findings show that the microwave transducer offers reliable and nondestructive moisture content evaluation, thus proving valuable insight for the preservation of cultural heritage materials.**

I. INTRODUCTION

For centuries, cultural heritage has been of great value as authentic witnesses that shed light on certain aspects of life and social dynamics of bygone eras. At the same time, increasing awareness of the vulnerability and deterioration of this material heritage underscores the need for conservation to ensure its preservation for future generations. Over the past two centuries, the debate on the need to preserve historical evidence has also involved the branch of philosophy concerned with aesthetics. The results of restorations carried out at different latitudes around the globe have been the focal point around which interventions have been organized for a long time.

In recent decades, however, it has become clear that the principle of "preventive restoration", as defined by Cesare Brandi [1], is the most desirable way to avoid extensive restoration of historic structures or artifacts. This approach involves a series of preventive measures designed to preserve the integrity of the cultural heritage and delay the need for full restoration, which is often traumatic for the artifact or work of art. These measures address both the natural deterioration of the materials used in the artwork and the need to control the environment in which the artifact is stored.

This principle has evolved into a concept now referred to as "planned maintenance". It involves organizing activities that allow for the natural aging process of materials, thereby minimizing invasive interventions on the artwork. The goal is to keep the artwork as close to its original state as possible, without the inevitable changes and transformations that occur during restoration.

In this context, environmental and structural monitoring using sensor technology is of paramount importance. The goal is to help preserve the artworks, ensure their longevity, and maximize their accessibility and appreciation by a wide audience. The aim of this work is to employ microwave transducers for the characterization of moisture content in cultural heritage materials. It is well established in the literature that the presence of water in building structures is one of the primary causes of masonry deterioration and is indeed considered one of the major factors to face in building preservation [2]. The measurement of moisture content and its distribution in walls is a critical factor in preventing the damage that water might cause to building structures. Although numerous techniques exist for the measurement of moisture content in buildings, many of them are unsuitable for use in cultural heritage constructions as they are based on procedures that can damage the valuable surfaces of the walls. Traditional moisture measurement techniques, in fact, require sample extraction, drilling holes, and probe insertion [2]. All these actions could potentially be more harmful than the consequences of the presence of water within the masonry. For this reason, the majority of research efforts are directed towards developing entirely noninvasive sensors and techniques that can be used freely on surfaces, without posing any risk of damage.

Nowadays, several methodologies have been validated to measure the percentage of humidity in historic masonry units, involving various sensors and techniques (e.g., magnetic resonance imaging, infrared thermography, electrical resistivity tomography, ground-penetrating radar, FBG optical sensors, time-domain reflectometry, among others [3]).

As an alternative, microwave sensors have been proposed as a viable substitute for classical methods due to their significant advantages [3, 4]. They are designed for contactless measurements, making them suitable for non-invasive solutions that are highly desirable in cultural heritage monitoring; they are low-power devices with low prototyping and fabrication costs. Moreover, they are inherently compatible with wireless technology, allowing them to be easily coupled with antennas and, thus, enabling remote sensing.

In this work, a microwave resonator is designed and fabricated with the aim of monitoring the moisture content of cultural heritage materials. The prototype is a two-port device operating in the frequency range from 2.25 GHz to 2.40 GHz. It is fabricated on a 1.6-mm-thick FR4 substrate using the inkjet-printing technique. The developed device allows contactless measurements for the evaluation of the moisture content inside concrete samples specially made for this research activity.

The remainder of the paper is structured as follows. Section II is divided into 2 subsections: the former reports a description of the device design and fabrication, while the latter includes a detailed description of the preparation of the samples used for the sensor test and characterization. The main obtained results are reported in Section III, while conclusive remarks are given in Section IV.

II. MATERIALS AND METHODS

This section is divided into two subsections. The first one is devoted to introducing the proposed microwave transducer for moisture measurements, whereas the second one is dedicated to the description of the samples used for preliminary tests.

A. *Proposed prototype*

The microwave sensor used in this study is composed by two capacitively coupled Split Ring Resonators (SRRs), designed using the microstrip technology. The adopted geometry is depicted in Fig. 1. Two 50-Ω microstrip lines serve as feedlines for the coupled resonators. This resonant structure has been previously implemented in several studies for sensing applications, where it showed outstanding performance in detecting NaCl in water and ice [5, 6], as well as in the characterization of biological samples [7]. The main advantage of this device lies in its ability to perform differential measurements, thereby significantly enhancing the robustness of the sensing process [7].

The resonant frequencies of the coupled resonator are determined by geometric parameters and the dielectric properties of both the resonator materials and the ambient environment surrounding the resonator. After the design is completed and the resonator is fabricated on its substrate, any changes in the permittivity of the surrounding environment continue to affect the device. This feature can be exploited for sensor design. In general, in a planar microwave resonant sensor, any change in the dielectric properties of the surrounding material is transduced into a modification of the electric field, which, in turn, causes a shift in the resonant frequency and/or a change in the quality (Q-) factor [8, 9, 10, 11].

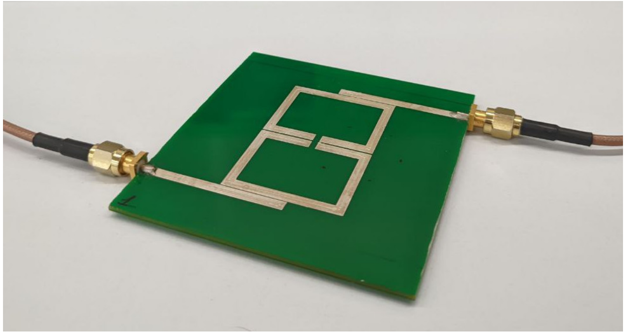
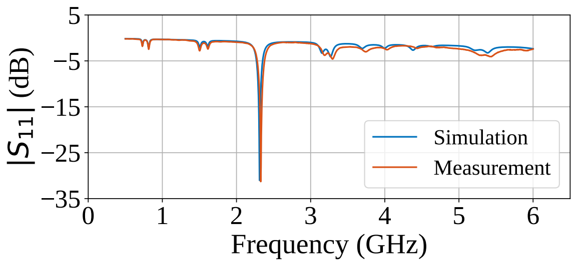


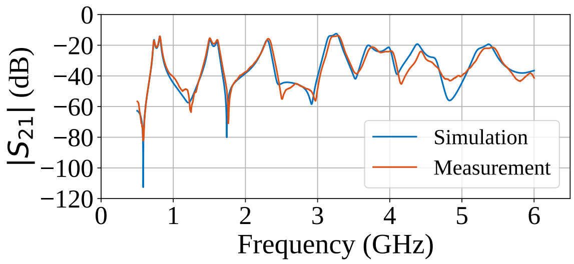
Fig. 1. Prototype after the printing process. The nominal board dimensions are: 80 mm × 80 mm × 1.6 mm.

The working principle of the microwave transducer presented here relies on the changes in the dielectric properties of the ambient environment surrounding the transducer itself. For example, a variation in the relative permittivity ε_r of a medium in close proximity to the microwave device leads to a modification in the resonance characteristics. This change is observed as a deviation in the key resonance parameters, namely the resonant frequency f_r, the quality ($Q-$) factor, and the amplitude or the reflection/transmission coefficient (A). Following a calibration procedure, these deviations can be linked to the ε_r of the material under examination. Consequently, f_r, Q, and A can be exploited to monitor changes in ε_r, which can be influenced by moisture content.

The sensor design process was carried out using professional computer-aided design (CAD) software. Once the design was finalized, the sensor was fabricated using an inkjet printing technique by means of the Voltera V-One PCB printer. A silver-based conductive ink (Voltera Conductor 2, nominal resistivity = $1.265 \times 10^{-7} \Omega{\cdot}$m [12]) is deposited on a 1.6-mm FR4 substrate using inkjet printing, to match the final sensor geometry (see Fig. 1). A uniform layer of silver-based conductive ink is applied to the back of the substrate to form the ground plane of the microstrip structure. The prototype is, then, cured in an oven at 200 °C for about 30 minutes, a crucial step that triggers the conductive ink chemical processes, enabling the metallic particles to combine and form a conductive layer. Subsequently, the sensor is cleaned with isopropyl alcohol and polished to remove any possible solvent residues or oxides. Finally, two SMA connectors are soldered to the ends of the two 50-Ω feedlines to accomplish the vector network analyzer (VNA) connection. The nominal dimensions of the FR4 board are: 80 mm × 80 mm × 1.6 mm.



(a)



(b)

Fig. 2. Comparison between simulated and measured (a) $|S_{11}|$ and (b) $|S_{21}|$ for the developed sensor over the frequency range from 500 MHz to 6 GHz.

The sensor is connected to the VNA to acquire the scattering ($S-$) parameters within the frequency range from 500 MHz to 6 GHz. It has been verified that, as a first approximation, the microwave resonator behaves as a symmetrical device, which implies that $S_{11} = S_{22}$ and $S_{21} = S_{12}$. For the purposes of this study, only the input reflection coefficient, i.e., S_{11}, is considered for data analysis. Fig. 2 presents a comparison between the simulated and measured $|S_{11}|$. Notably, in the examined frequency range from 500 MHz to 6 GHz, there is a very good agreement between simulation and measurement. Furthermore, $|S_{11}|$ exhibits a pronounced dip around 2.33 GHz, characterized by a quality factor of 730 ± 20. This value is significantly higher compared to the other dips that occur at different frequencies, making the dip at 2.33 GHz a good candidate for sensing applications.

B. Samples preparation

Three samples with identical nominal geometric dimensions (i.e., 100 mm $\times$ 100 mm $\times$ 40 mm) but different compositions were considered in this study. The three samples contain different proportions of basalt sand and hydrated lime. The sand in the three samples is characterized by specific granulometries, with typical grain sizes up to 2.8 mm. In addition, sample 2 contains marble dust with a granulometry of less than 1 mm. Sample 3, on the other hand, contains both holvere and sand with a granulometry of less than 0.3 mm.

Fig. 3. Prepared samples in their wooden formwork. The variations in color between samples are due to differences in material composition.

This variation in composition among the samples enables a thorough analysis of how different materials react to moisture content. Furthermore, it allows for an investigation into whether these compositional differences result in observable changes in the drying patterns of the samples over time. Upon their preparation, the three lime/water mixtures were cast in wooden formwork, as shown in Figure 3, to enable them to dry, yielding samples with specific geometric dimensions. The samples were removed from the formwork on the second day after their preparation to further decrease their water content, thereby enhancing their strenght and robustness. The measurement campaign started three days later, i.e., after 5 days of samples preparation.

III. EXPERIMENTAL ACTIVITY

The measurement setup consists of the Agilent 8753ES VNA, to which the microwave transducer is connected using two 50-Ω coaxial cables (see Fig. 4). The VNA was calibrated employing the full two-port Short-Open-Load-Thru (SOLT) method. Measurements are performed contactlessly, with the samples not directly touching the microwave transducer. As a matter of fact, they are kept at a consistent distance of approximately 8 mm using a set of plastic spacers. This ensures measurement consistency, as the distance between the sample and the sensor influences the results.

Measurements started five days after the preparation of the samples to ensure sufficient mechanical resistance of the samples and to prevent cracking phenomena during the measurement process. Over time, the $S-$ parameters of the microwave transducer were acquired, and the resonant frequency, Q-factor, and dip amplitude were evaluated.

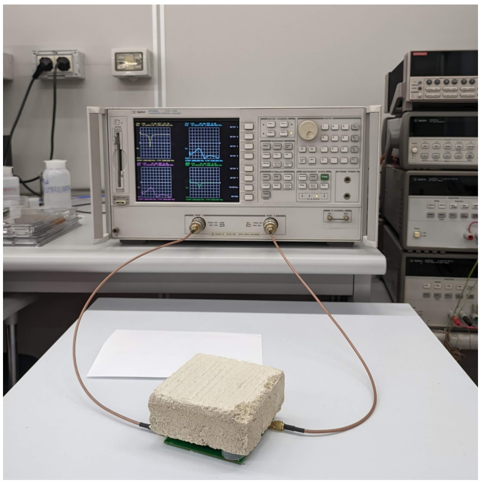


Fig. 4. Photo of the measurement setup. The prototype is connected to the Agilent 8753ES through two coaxial cables and is loaded by Sample #3.

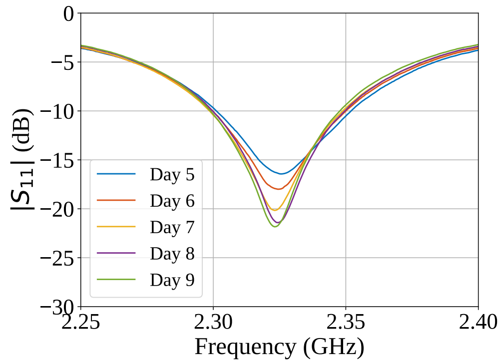


Fig. 5. Change of the magnitude of the S_{11} parameter from day 5 to day 9 for Sample #3. A clear variation in the dip amplitude as well as in the dip Q-factor can be observed.

Fig. 5 illustrates the $|S_{11}|$ variation for Sample #3 over the first five days of measurements. A clear trend can be observed in the estimated dip amplitude (i.e., from -16.4 $\pm$ 0.05 dB to -21.9 $\pm$ 0.1 dB), as well as in the Q-factor (i.e., from 88 $\pm$ 1 to 195 $\pm$ 3) and resonant frequency (i.e., from 2.3251 $\pm$ 0.0002 GHz to 2.3233 $\pm$ 0.0002 GHz). These parameters were evaluated using a fitting procedure based on a complex Lorentzian fitting, similar to the approach previously used in [13]. The corresponding measurement uncertainties were assessed by combining contributions from the VNA, the fitting procedure, measurement repeatability (i.e., multiple measurements under identical conditions), and measurement reproducibility (i.e., multiple measurements with slight alterations in the sample positioning).

In this study, data refer to measurements conducted over two weeks following the preparation of the three samples. For the sake of space, only the results concerning the variation in dip amplitude are here discussed. Fig. 6 presents the temporal variation in dip amplitude for the three samples. A decreasing trend for the dip amplitude can be observed during the first week, with a slope of -0.80 dB/Day, -0.43 dB/Day, and -1.44 dB/Day for Sample #1, #2, and #3, respectively. Conversely, during the second week, it appears that the samples have expelled most of their water content and the evaporation rate has significantly decreased. Indeed, the variation in dip amplitude maintains a fairly linear trend, but the slope is lower this time, i.e., -0.12 dB/Day, -0.08 dB/Day, and -0.11 dB/Day for Sample #1, #2, and #3, respectively.

IV. CONCLUSIONS

This work focused on the design, fabrication, and testing of a microwave transducer aimed at a contactless and non-invasive method to monitor the moisture content in cultural heritage materials. The proposed prototype operates in the microwave range and was fabricated on a low-cost FR4 substrate using an inkjet printing technique. The sensor was tested on specially made samples showing a clear trend of the $|S_{11}|$ with the moisture content of the prepared samples thus demonstrating a reliable and practical solution for moisture content monitoring in cultural heritage contexts. While this work represents a preliminary investigation, the proposed prototype represents a potential advancement in the field of cultural heritage preservation. Its non-invasive, non-contact, and low-cost nature offers a promising approach to moisture detection in historical structures. This, in turn, supports preventive maintenance strategies that contribute to the long-term preservation of cultural artifacts. Further activities are underway with the aim of performing a complete sensor characterization and calibration, thus exploring the sensor capabilities in real-world settings.

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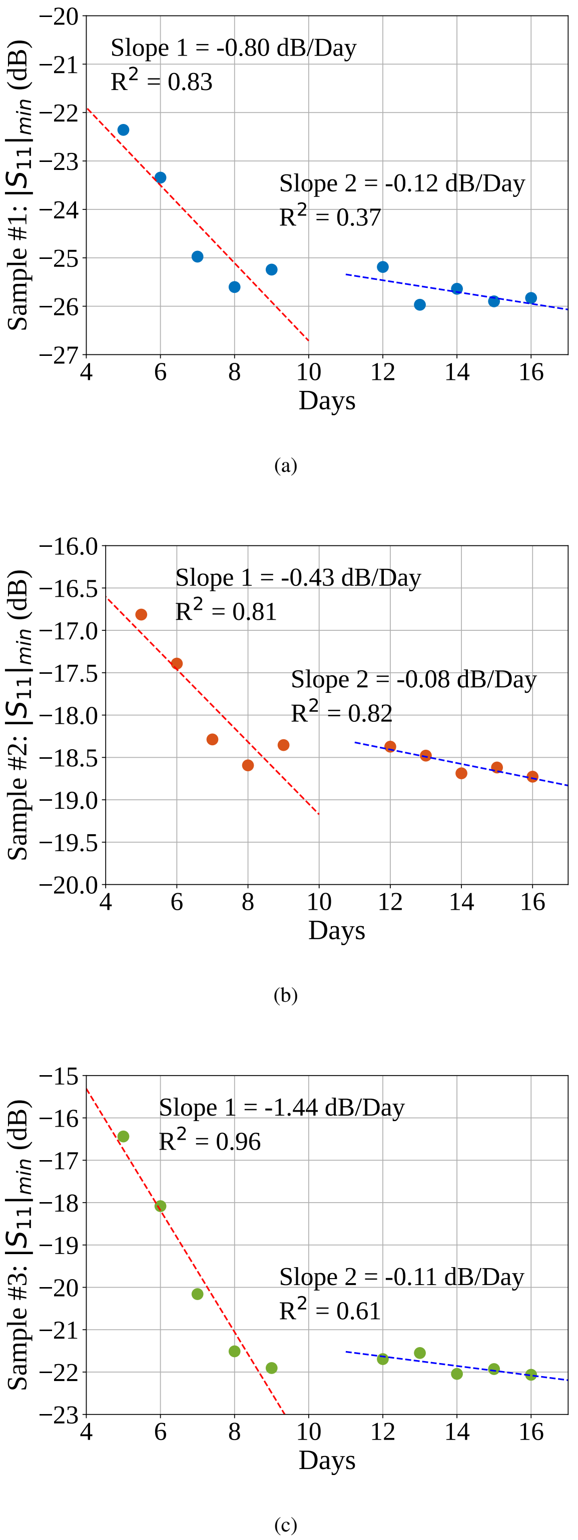

Fig. 6. Variation in dip amplitude over time from Day 5 to Day 16 for (a) Sample #1, (b) Sample #2, and (c) Sample #3. The red and blue dashed lines represent the linear regressions calculated from the measurements taken during the first and second week, respectively.

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